When Beer is Safer than Water: Beer Availability and Mortality from Waterborne Illnesses in 18th Century England

Francisca Antman and James Flynn

Univ. of Colorado, Boulder

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Abstract

We investigate the impact of beer on mortality during the Industrial Revolution. Due to the brewing process, beer represented an improvement over available water sources during this period prior to the widespread understanding of the link between water quality and human health. Using a wide range of identification strategies to derive measures of beer scarcity driven by tax increases, weather events, and soil quality, we show that beer scarcity was associated with higher mortality, especially in the summer months where mortality was more likely to be driven by water-borne illnesses. We also leverage variation in inherent water quality across parishes using two proxies for water quality to show that beer scarcity resulted in greater deaths in areas with worse water quality. Together, the evidence supports the hypothesis that beer had a major impact on human health during this important period in economic development.

1. Introduction

The critical importance of access to clean water for human health and economic development has been underscored in policy circles (UN General Assembly (2015)) and economic research alike (Kremer et al. (2011); Galiani, Gertler, and Schargrodsky (2005); Devoto et al. (2012); Ashraf et al. (2017)). However, much less attention has been paid to alternatives to drinking water, which may have contributed to human health long before the availability of modern water purification technologies, and thus to the economic development of the world as we know it today. In areas of the world where widespread adoption of water improvement technologies remain out of reach, much can still be learned from this historical experience. This paper provides the first quantitative estimates into one well-known water alternative that may have ultimately proven to be the most impactful for economic development–beer during the Industrial Revolution in England.

Although beer in the present day is regarded primarily as a beverage that would be worse for health than water, several features of both beer and water available during this historical period suggest the opposite was likely to be true. First, brewing beer would have required boiling the water, which would kill many of the dangerous pathogens that could be found in contaminated drinking water. As Bamforth (2004) puts it, 'the boiling and the hopping were inadvertently water purification techniques' which made beer safer than water in 17th century Great Britain. Second, the fermentation process which resulted in alcohol may have added antiseptic qualities to the beverage as well (Standage (2006), Ingram and Buttke (1985)). Homan (2004) notes that "because the alcohol killed many detrimental microorganisms, it (beer) was safer to drink than water" in the ancient near-east[1]. This property of beer could benefit drinkers even if contaminated water was added to it. Sheth, Wisniewski, and Franson (1988) ran an experiment where they added Salmonella, Shigella, and enterotoxigenic Escherichia coli to different beverages and mon-

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[1] Similarly, when describing how beer protected drinkers during the London cholera epidemic, Glaeser (2012) notes that "nearby ale imbibers remained healthy; alcohol's ability to kill waterborne bacteria had long helped city dwellers avoid illness."

itored survival of the pathogens. While beer did not perform as well as red wine, fewer of the pathogens survived in beer than in water or milk. Additionally, beer drinkers could be protected from from bacteria they consume elsewhere because of the alcohol content in their stomachs. Observational studies have shown that alcohol drinkers appear to be less vulnerable to Helicobacter pylori (Brenner et al. (1999)), Hepatitis A (Desenclos et al. (1992)), and Salmonella (Bellido-Blasco et al. (2002)). Third, beer in this period, which sometimes referred to as "small beer," was generally much weaker than it is today, and thus would have been closer to purified water. Accum (1820) found that small beer in late 18th and early 19th century England averaged just 0.75% alcohol by volume, a tiny fraction of the content of even the 'light' beers of today. While this may have reduced the potential antiseptic qualities of the beer, it also meant that beer in this period was far less harmful to the liver. Taken together, these facts suggest that beer in this period had all of the benefits of highly purified water with virtually none of the health risks associated with beer consumption today. In contrast, the quality of plain water in this period, before the establishment of modern sanitation infrastructure and water purification technologies, would have been much more likely to be contaminated by sewage and pathogens, unknowingly contributing to cholera and typhoid outbreaks which were mistakenly thought to be caused by miasmas (Johnson (2006)) until John Snow's famous discovery that contaminated water from the Broad Street pump in London was behind the spread of cholera in the 1840s (Snow (1855)). Thus, even though people did not recognize beer as a healthful choice, drinking beer would have been an unintentional improvement in beverage over regular water, and thus may have contributed to improvements in human health and economic development over this period which we investigate here.

While beer has a long history in England that pre-dates the Industrial Revolution (Clark (1998)), to gauge the impact of beer as an alternative beverage we focus instead on limits to the availability of beer during a critical time period for economic development, and examine its impacts on mortality. This approach allows us to make use of several key pieces of data, including a malt price series and tax hike which effectively limited the availability of beer. We also incorporate data on rainfall which would have affected barley production, a necessary ingredient into the production of beer. Thus, we leverage weather shocks which would also have resulted in the relative scarcity of beer. In additional specifications, we make use of information on soil type, which would have affected whether or not barley was grown in a region. We compare areas in which barley, and thus beer, would have been more readily available to areas in which it was relatively scarce. Following Antman (Forthcoming), we also compare areas where water quality was inherently worse to areas where it was inherently better based on two alternative geographic measures and, as expected, observe more severe impacts of beer scarcity on mortality in areas with worse water quality. To address concerns that our identification strategy may be picking up the effects of food scarcity, we show that the seasonality of these mortality events matches the summer months, when water-borne mortality crises were at their peak, and not winter months, when deaths from starvation were more likely to occur. Event studies showing mortality rates in parishes with low and high water quality before and after the malt tax increase show larger increases in mortality rates in low water quality parishes after beer became more expensive. These graphs are consistent with the proposed mechanism, and show no evidence of pre-existing trends in mortality prior to the malt tax increase, suggesting our results are robust to concerns over parallel trends. To address the possibility that alternative explanations might be driving our results, we also control for regional wages and tea imports to rule out correlated effects driven by the availability of tea which would have been another improvement over drinking water (Antman (Forthcoming)). Through all these approaches, we find evidence consistent with the hypothesis that relative scarcity of beer resulted in higher mortality during this critical period for economic development.

This paper connects closely with the literature examining the importance of drinking water sources for human health and economic development. However, quantifying the role of water in shaping economic development is complicated by the fact that its importance is so well-known, thus the specter of selection bias in many estimated treatment effects. While explicitly randomized controlled trials may be feasible to evaluate short-term impacts in some settings (Kremer et al. (2011)), barriers to adopting water quality interventions often remain (Zinn et al. (2018)) and thus raise questions about their long-term impacts. Historical evaluations of large-scale water interventions in the U.S. present an alternative (Alsan and Goldin (2019); Beach et al. (2016); Ferrie and Troesken (2008); Cutler and Miller (2005); Troesken (2004)), however, the simple fact that they were implemented as public health interventions suggest that the link between water and health was already well established by the period of time in which they were undertaken, thus again raising the issue of potential endogeneity and selection bias. This paper provides an important research alternative, since the period precedes the modern understanding of the germ theory of disease and widespread understanding of the link between water and human health (Johnson (2006)). As such it connects closely with Antman (Forthcoming) which shows the impact of tea on mortality in England. We follow a similar approach, but in examining the impact of beer, shed light on an important alternative to water with a long history in England that helped pave the way for economic development. While we are not the first ones to hypothesize the impact of beer on economic development (see for example Standage (2006)), to our knowledge this paper represents the first quantitative analysis.

The paper proceeds as follows. Section 2 provides background information on beer production in England and mortality rates in England that underlie our identification strategy. Section 3 presents the data used in the analysis. Section 4 presents the methodology and results. Section 5 concludes.

2. Background

Our multiple identification strategies rely on several important facts about beer production and deaths related to water-borne diseases. First, beer production is largely dependent on the availability of malt, one of the four main ingredients in beer[2]. According to Clark

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[2] The others being water, yeast and hops

(1998), malt made up approximately two-thirds of the cost of beer production through the 19th century. Therefore, when malt is abundant and cheap, beer tends to be as well, and vice versa. Second, as malt is made of barley, malt production depends almost entirely on the yield of the barley crop. This means that the availability of beer for consumption is correlated with the suitability of a year's weather for growing barley. During overly wet growing seasons, barley yields decline, leading to less malt and less beer being produced. Third, barley grows best in fertile loam soil, which is most common in the gley soils[3]. Nearly half (48.4%) of parishes in the malt-producing hub East Anglia[4] are classified as having gley soil, while only 16.9% of parishes outside of East Anglia have gley soil. This means that beer would be more commonly available in areas with gley soils. Before railroads became ubiquitous in the United Kingdom in the middle 19th century, it was difficult and expensive to transport barley long distances. Though we do not have data on the geographic variation in prices, it seems reasonable to believe that this would cause beer to be cheaper and more abundant in areas where barley was grown. Subsequently, because our causal mechanism relies on people replacing water consumption with beer consumption, this is likely most common in areas with gley soil, where beer was relatively more abundant in the first place. These areas should also be more susceptible to increased deaths from water-borne illnesses due to negative shocks in beer availability. Fourth, regarding the prevalence of deaths from water-borne illnesses, the quality of available water is an important determinate of the likelihood of contracting such a disease. Therefore, parishes with few nearby sources of running water and low-altitude parishes are more susceptible to water-borne illnesses than higher altitude parishes and parishes with several nearby sources of running water. Finally, while starvation deaths from a poor crop yield occur throughout the year and may be especially pronounced during winter months, water-borne illness deaths are concentrated in the late summer months. This allows us to deal with the identification threat of high rainfall causing both low barley yield and low yield for other staple British crops leading to starvation by focusing on the seasonal pattern of

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[3] https://www.landis.org.uk/downloads/downloads/Soil˙classification.pdf

[4] This region includes the counties of Norfolk, Suffolk and Cambridgeshire in the east of England

deaths. If deaths are exhibited in winter months or spread more evenly throughout the year, they can more likely be attributed to starvation, whereas if they are concentrated in July-September, they are more likely due to water-borne illnesses.

To illustrate this pattern, Figure 1 compares average monthly mortality rates across England before and during the 1831-1832 cholera pandemic (Chan, Tuite, and Fisman (2013), Burrell and Gill (2005)) and around the Pan-European famine which affected much of Western Europe, including Britain, from 1585-1587 and 1590-1598. The left panel of Figure 1 shows that from 1800-1830, average mortality peaked in the winter months of January-April before declining to a trough in the summer months of July-September. Similarly, in 1831-1832, during the cholera pandemic, there is a peak in the winter months, and deaths begin to decline in the springtime. In contrast, however, deaths rise once again in the summer months of July-September during the cholera pandemic, while they reach their lowest points in the non-cholera years. The right panel of Figure 1 shows average monthly mortality from 1580-1600 for famine years (1585-1587, 1590-1598) versus non-famine years (1580-1584, 1588-1589, 1599-1600)[5]. Average mortality is higher in famine years across the board, not just during one particular season. If anything, deaths appear to be most pronounced in December, March and April. These trends allow us to separate the impacts of starvation-related deaths from water-borne illness deaths by looking for clusters in the summer months only. Similarly, Appendix Figure 1 displays Figure 2 from Saad et al. (2018), which traces the seasonality of modern typhoid cases in different regions. In Europe, approximately 50% of total cases occur between July and October, with only around 20% of cases occurring between January and April.

3. Data

We combine data from several sources in order to estimate the impact of beer availability on deaths from water-borne illness in 18th and 19th century England. First, we construct mortality rates and other parish-level characteristics using Wrigley and Schofield (2003)'s

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[5] Alfani and Gráda (2018) and McNicoll (2018)

collection of records on burials, baptisms, and marriages. These records include data on 404 parishes covering the years 1538-1849. Using these data, we follow the methodology from Wachter (1998) to impute population counts for each parish-year combination as a weighted average of previous years burials, baptisms, and marriages.

We proxy for water quality in multiple ways following Antman (Forthcoming). First, we use the average elevation of each parish, constructed by combining Shuttle Radar Topography images (Jarvis et al. (2008)) with historical parish boundaries (Southall and Burton (2004)). Our reasoning behind using this measure is that all else equal, the higher elevation parishes are likely to have cleaner water because they will be less contaminated by runoff from their lower-elevation neighbors. Second, we use the number of running water sources available in an area, as given by the main rivers within three kilometers of the parish, which was calculated using data from the United Kingdom Environment Agency Statutory Main River Map of England overlaid on a map of historical parish boundaries (Burton, Westwood, and Carter (March 2004); Southall and Burton (2004)). Our reason for using this measure is that having greater natural sources of running water would have been critically important for obtaining clean water during this period before water infrastucture projects became commonplace. Of course, both of these geographic measures may be correlated with economic development independently, and thus, we emphasize that we are focused only on their impact on mortality through their interaction with measures capturing the availability of beer.

As part of our multiple identification strategies, we exploit two plausibly exogenous sources of variation in the availability of beer. First, we use a change to the British Malt Tax which ocurred in 1780 (Stopes (1885)). If higher malt taxes lead to beer becoming more scarce in certain years, we might expect people to substitute from drinking beer to drinking water, leading to increased deaths due to water-borne illnesses, especially in areas where water quality is lower. Our other source of variation in the availability of beer is due to weather. We use data from Briffa, Schrier, and Jones (2009) which identifies historical weather patterns using the Palmer Draught Severity Index (PDSI). These data are available for London from 1697-2000. The PDSI is a measure of regional moisture availability that has been used extensively to study historical wet and dry spells. The PDSI classifies each month on a scale from -4 (extremely dry) to 4 (extremely wet). As extremely wet growing seasons are detrimental to barley yield, we can expect beer to be more scarce in years with a higher PDSI during the barley growing months.

4. Methods and Results

4.1. *Malt Tax Increase of 1780*

We begin by analyzing the effects of a large increase in the malt tax, which occurred in 1780. Prior to 1780, the malt tax had not been raised since 1760 and was only .75 schillings per bushel (6 schillings per quarter), which represented about 20% of the 1779 selling price of brown malt (28.83 schillings according to Mathias (1959)). In 1780, the malt tax nearly doubled to 1.35 schillings per bushel (10.8 schillings per quarter). At the time, this represented the largest hike in the tax since its inception in 1697. By focusing on what happened to summer and winter death rates in the years surrounding this large increase, we can get a better idea of how important beer was for public health at the time. Of particular interest is what happens in parishes with better versus worse water quality when beer becomes more scarce. If the tax caused individuals to substitute from beer to water, we would expect to see relative increases in summer deaths in parishes with poor water quality. We look into this by running models of the following form:

$$\begin{aligned} SummerDeaths_{it} = \beta_1 * LoWaterQual_i * Post_t + \beta_2 * HiWaterQual_i \\ * Post_t + \beta_3 * X_{it} + \mu_i + \delta_t + \psi_i * t + \epsilon_{it} \end{aligned} \tag{1}$$

Where $SummerDeaths_{it}$ is the log of burials in parish i in the summer of year t, $LoWaterQuality_i$ is an indicator for whether the parish has below the 25th percentile in a measure of water quality (we use both elevation and number of nearby sources available), while $HiWaterQuality_i$ is an indicator for being above the 75th percentile in water quality, and $Post_t$ is an indicator for being after the 1780 malt tax increase. X_{it} is a vector of control variables that we expect to impact the number of summer deaths. These include logs of the estimated parish population, the average parish wages, the quantity of tea imports. We also include the number of deaths occurring in the winter to control for factors which influence death rates throughout the year. μ_i is a parish fixed effect, δ_t is a year fixed-effect and $\psi_i * t$ is a parish-specific time-trend. We use $t = 1770, 1771....1790$. The parameters of interest, β_1 and β_2, therefore measure how well the low water quality and high water quality parishes did in comparison to the parishes with average levels of water quality in response to the tax increase. If the effect of water quality on mortality is monotonically decreasing in water quality, we would expect summer deaths in the low water quality parishes to increase in response to the malt tax relative to higher water quality parishes as low quality parishes are forced to substitute from beer towards more dangerous water sources. We would therefore expect a positive β_1 and a negative β_2 Results for this model using the number of water sources available and then altitude as the measure of water quality are displayed in Table 1.

Column 1 of the top panel of Table 1 shows the results for parishes with few available water sources compared with all others. In the years following the malt tax increase, these parishes see a 16.5% rise in the summer death rate, with a p-value of .006. Conversely, column 2 shows that parishes with the most available water sources, which should be the more protected from the dangers of contaminated water, see their summer death rates fall by 14.6% relative to all other parishes (p-value = .006). When both interaction terms are included in the model, we see that the difference between the two coefficients suggests that the summer death rate in low water quality parishes increases by 22.2% relative to high water quality parishes, with a p-value on the equality of the two coefficients of .001. Columns 4-6 replicate columns 1-3 with the ratio of summer versus winter deaths on the left-hand side, and the economic inference is similar. After the malt tax increase went into effect, summer deaths in low water quality areas rose relative to winter deaths, while high water quality parishes did comparatively better than medium and low water quality parishes, potentially because switching from beer to water consumption is less costly when the water quality is better. Appendix Table 1 displays a falsification version of this model, which replaces the summer death rate with the winter death rate on the left hand side and replicates columns 1-3 of Table 1. All of the interaction terms in Appendix Table 1 are insignificant and close to zero, suggesting that the changes which took place in the years following the increase in the malt tax mainly affected the summer death rates, consistent with our hypothesis.

The bottom panel of Table 1 displays results replacing the number of nearby water sources with altitude as a measure of water quality. Results are similar qualitatively, with low quality water parishes seeing much higher summer death rates. In this case, being in the bottom quartile of altitude was associated with a 12.3% increase in the summer death rate, while being in the top quartile of water sources was associated with a relative 12.2% decrease in summer deaths. The difference between the coefficients in column three suggests that low altitude parishes saw summer death rates rise by 18.6% relative to high altitude parishes (p-value = .018). Columns 4-6 again replicate columns 1-3, switching summer deaths with the ratio between summer and winter deaths on the left-hand side. Again, the results are qualitatively similar, though the p-value on the difference between the two coefficients when both are included is now only .146. There is little correlation between the two measures of water quality, so the similarity in results is not driven by the same parishes being identified in both samples[6] Appendix Table 2 displays the falsification test, switching summer and winter deaths on the left hand side. Once again, all of the coefficients are much smaller in magnitude and insignificant, indicating that the increased death rates which occurred in low water quality parishes after the malt tax was increased mainly took place during the summer months. Finally, the bottom panel of Table 1 displays results on the intersection of the two water quality measures. $Low * Low * Post$ measures the change in summer mortality for the 31 parishes with both low altitude and a low number of water sources, while $High * High * Post$ tracks the 30 parishes with high altitude

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[6] For example, of the 100 parishes considered low altitude, 31 of them are considered to have a high number of water sources, 22 of them are considered to have low water sources and the other 57 are neither. Of the 103 high altitude parishes, 30 have a high number of water sources, 28 have a low number of water sources and 45 are neither.

and a high number of water sources. If our hypothesis is correct, parishes which have poor (high) water quality on both metrics should be especially exposed (protected). The results are consistent with this story, as all of the coefficients are larger in magnitude and significance than their counterparts, suggesting that the parishes with the worst water quality were especially exposed to this increase in the malt tax.

4.2. Soil Interaction

Focusing instead on areas where beer production was most common, and therefore most vulnerable to malt tax increases, we run similar models to see whether parishes with gley soil suffered relatively more summer deaths in response to the increase in the malt tax. We do this by estimating models of the following form:

$$SummerDeaths_{it} = \beta_1 * GleySoil_i * Post_t + \beta_3 * X_{it} + \mu_i + \delta_t + \psi_i * t + \epsilon_{it} \tag{2}$$

for $t = 1770, 1771.....1790$. In this model, $GleySoil_i$ is an indicator for parish i having gley soil. We continue to control for the same vector of covariates from the previous specifications. Results from this model are displayed in Table 2. In columns 1-3, parishes with gley soil had summer death rates which increased by approximately 18% after the malt tax was implemented relative to parishes without gley soil. Appendix Table 3 displays the falsification test which switches summer and winter deaths on the left hand side. The effects are all less than one third as large as in the main specification and are all insignificant. Taken together, the results from this section show strong support for our hypothesized mechanism operating through the availability of beer. Moreover, in order for our hypothesis not to be correct, there would have to be some other factor which simultaneously precipitated an increase in summer deaths in low altitude parishes, parishes with few water sources, and parishes with gley soil, immediately after the increase in the malt tax in 1780. While impossible to completely rule out, such a factor seems unlikely to exist, and thus further bolsters our hypothesis.

4.3. Event Study

Recently, difference-in-differences estimation models like equation (2) have come under scrutiny for a variety of reasons. Since we are examining a single treatment whose timing is constant across parishes, several of the recent criticisms in this literature which concern difference-in-difference specifications with staggered treatment timing (Goodman-Bacon (2021), Sun and Abraham (2021), Callaway and Sant'Anna (2021)) do not apply to this setting[7]. We are concerned, however, with the previous specifications inability to separate a treatment effect from a pre-existing trend that was already occurring between the two groups, making it difficult to evaluate the equal counterfactual trends assumption that is inherent to these specifications. For example, a valid concern is that summer deaths may have decreasing in high water quality parishes relative to low water quality parishes throughout the sample period, and that the results from above may be driven by that relationship. Since the difference-in-differences estimator is essentially comparing changes in conditional means across two periods, such a trend would wrongfully be picked up as a treatment effect. One way to deal with this issue is by using event-study designs which allow the treatment effect to vary in each year. This allows for the inclusion of pre-treatment indicators, which can identify any problematic pre-treatment trends and demonstrate that the two groups were on similar trajectories before the treatment went into effect. To this end, we estimate models of the following form:

$$SummerDeaths_{it} = \sum_{k=-5}^{6} \theta_k (ParishType_i * Post_{t,t+k}) + \beta * X_{it} + \mu_i + \delta_t + \psi_i * t + \epsilon_{it} \quad (3)$$

where the only difference from equation (2) is that now we estimate separate treatment effects for five years before and six years after the malt tax increase went into effect. We estimate this model separately for low water sources parishes, low altitude parishes, parishes with gley soil, and parish which both low water sources, low altitude and gley

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[7] For example, Goodman-Bacon (2021) addresses situations where early-treated units are being used as controls for later-treated units and vice-versa, which is not possible here. Sun and Abraham (2021) show that in settings with variation in treatment timing across units, the coefficients leads or lags can be contaminated by effects from other periods, which causes problems in assessing pretrends. Finally, Callaway and Sant'Anna (2021) study identification of DiD models with multiple time periods and variation in treatment timing.

soil. Ideally, the coefficients should all be close to zero and insignificant in the periods before the intervention. Then, shortly after the malt tax was raised in 1780, we should see relative increases in summer deaths in each specification.

Figures 2 displays these estimates for all four groups. The top left graph displays the estimates for the parishes with few nearby water sources. From 1775-1778, the coefficients are all small in magnitude and insignificant, with the smallest p-value of .66. A test on the joint significant of the 1775-1778 coefficients yields a p-value of .93. There is a slight uptick in 1780, but then a large and significant increase of .2 log points in 1781. After that, all the subsequent coefficients are positive and remain between .04 and .25. A test on the joint significance of the 1781-1784 coefficients yields a p-value of .03. The top right graph displays estimates on the low altitude parishes, and the results here are perhaps the weakest of the four. Still, however, the coefficients are around zero and all insignificant in the pre-period, with increases in summer mortality directly after the tax went into effect in 1780. A test for joint significance on the 1775-1778 coefficients yields a p-value of .42, while a test on 1781-1784 yields a p-value of .05. The bottom left graph repeats this exercise for the parishes with gley soil and the results are similar. There does not appear to be much of a pretrend, though the 1776 coefficient is negative and borderline significant on its own. A test of joint significance on 1775-1778 yields a p-value of .12. After 1780, the coefficients are all positive and rise up to a peak in 1783 before leveling off and reverting somewhat. A test of joint significance on the 1781-1784 coefficients yields a p-value of .002. Finally, the bottom right graph estimates equation (3) on the parishes which have few water sources, low altitude and gley soil. The results are once again similar, with little evidence of pretrends before 1780 (p-value of .76 for 1775-1778), and then substantial increases in summer mortality for these most-exposed parishes after the increase in the malt tax (p-value of .015 for 1781-1784). Across all four specifications, it is clear that very little was happening in the years leading up to the malt tax hike of 1780, but then large increases in summer mortality occurred in the parishes who were most exposed to the effect of the tax shortly thereafter.

4.4. Yearly Rainfall Interactions with Water Sources and Soil Type

Finally, we demonstrate that in rainier barley growing seasons, which are less conducive to barley growing, summer deaths rise relative to winter deaths, with these effects concentrated in areas where the most barley is produced and areas where water quality is poorest. This is consistent with our proposed mechanism that decreased availability of beer leads people to substitute drinking beer with drinking water, which leads to an increased risk of contracting a water-borne illness. We do this by estimating models of the following form:

$$\begin{aligned} lnSummerDeaths_{it} = \beta_1 * Rain_t * LowSources + \beta_2 * Rain_t * GleySoil + \beta_3 * Rain \\ * GleySoil * LowSources \beta_4 * X_{it} + \mu_i + \delta_t + \psi_{i*t} + \epsilon_{it} \end{aligned} \tag{4}$$

where $lnSummerDeaths_{it}$ is the log of summer burials for parish i in year t. $Rain_t$ represents the Palmer Drought Severity Index, a measure of historical rainfall, for London in during the main barley-growing months of February through May in year t. The PDSI ranges from about negative four (exremely dry) to positive 4 (extremely wet). Since overly wet barley growing seasons are bad for barley production, large positive values of the PDSI will lead to a decreased crop yield. The three interaction terms, $Rain_t * LowSources$, $Rain_t * GleySoil$, and $\beta_3 * Rain * GleySoil * LowSources$ measure whether rainier seasons are more impactful to summer death rates in areas with few nearby water sources and in areas with gley soil, where barley production is most common. If rainy barley growing seasons lead people to consume more unsafe drinking water, we would expect all three coefficients to be positive. The rest of equation (4) is similar to our previous models. Because our rain data is for London, we only look at the counties which surround the London metropolitan area[8], and we exclude altitude as a measure of water quality here because there is substantially less variation in altitude across these counties. Results from these specifications are reported in Table 3.

In column 1, the interaction term measuring the effect of rainier barley growing seasons on parishes with few nearby water sources is positive and significant, indicating

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[8] We include the counties of Buckinghamshire, Surrey, Berkshire, Essex, Herfordshire, Kent, Middlesex, Bedfordshire, Cambridgeshire, Huntingdonshire, Hampshire, Norfolk, Oxfordshire, Suffolk and Sussex

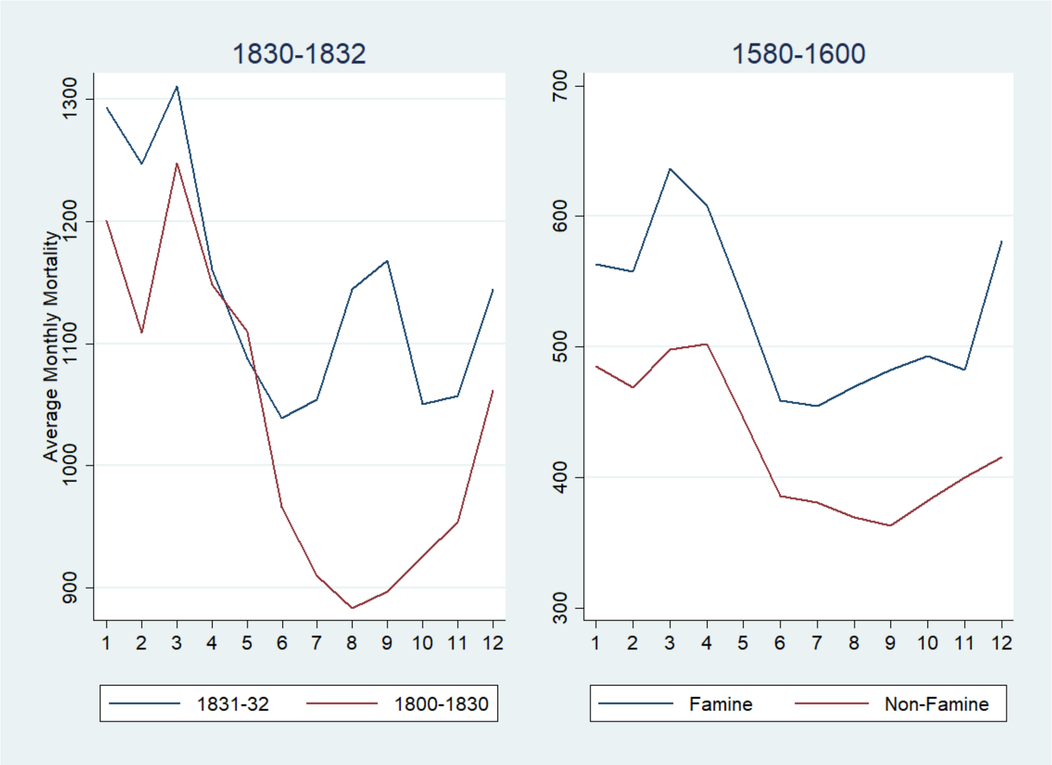
that summer deaths rise following particularly rainy barley growing seasons. Column 2 replaces the $Rain * Sources$ interaction with $Rain * GleySoil$, demonstrating that rainy barley-growing seasons lead to more summer deaths in areas where beer is most abundant, even controlling for the number of deaths occurring in the winter months. Column 3 includes both interaction terms to address concerns that maybe they are just highly correlated, which is why they both seem to be positive and significant. Even when included separately, both remain positive and significant at .1. Column 4 includes a joint interaction term, $Rain * Gley * Sources$, which measures the effect of rainy barley-growing seasons on parishes with gley soil and few nearby water sources, and the effect here is largest in both magnitude and significance, suggesting that these parishes are particularly vulnerable. Column 4 replaces the log of summer deaths on the left-hand side with the ratio between summer and winter deaths and the effect is still positive and significant, indicating that these effects are acutely felt during the summer months and not year-round, as our hypothesis would predict.

5. Conclusion

Through a panoply of evidence and several identification strategies, this paper provides the first quantitative evidence of the importance of beer to human health during the Industrial Revolution in England. As demonstrated here, the relative scarcity of beer, whether driven by higher prices, a tax hike, geographical variation, and/or weather events, contributed to rising deaths in England. Moreover, the seasonal pattern of deaths suggest these mortality events were not driven by starvation, but by water-borne diseases which had larger impacts when beer was relatively scarce. The estimates showing disparate impacts across low and high water quality areas, using two different proxies for water quality, also suggest that the root cause of the variation in mortality associated with beer was indeed driven by water quality as opposed to some other explanation.

While this research highlights the importance of alternative beverages to human history, it also underscores the importance of access to clean water for human health and economic development today. In areas of the world where widespread adoption of water improvement technologies remain out of reach, much can still be learned from this historical experience. In particular, harnessing culture and custom to drive the adoption of an alternative beverage or health technology may ultimately prove to be most impactful for economic development.

Figure 1 — Average Monthly Mortality Around Major Crises in Britain



Note: This figure displays monthly average mortality during and around two crises in British history. The left graph displays mortality before and during the 1831-32 cholera outbreak. The blue line shows that during the outbreak, mortality was similar to the years prior except in the late summer months, where mortality during the cholera crisis peaked. Conversely, the graph on the right shows British mortality around the Pan-European famine of the 1580s and 1590s (1580-1584, 1588-1589, 1599-1600 were the famine years). Unlike in the cholera epidemic, mortality during the famine years appears higher than the non-famine years in all months, especially December, February and March.

Table 1 — Water Quality - Malt Tax Interaction Model, 1770-1790

	(1)	(2)	(3)	(4)	(5)	(6)
	Smr Dths	Smr Dths	Smr Dths	Ratio	Ratio	Ratio
Low Sources * Post	0.165^{***}		0.129^{*}	0.261^{**}		0.244^{**}
	(0.0601)		(0.0660)	(0.106)		(0.118)
High Sources * Post		-0.146^{***}	-0.0929		-0.145^{*}	-0.0437
		(0.0532)	(0.0585)		(0.0862)	(0.0979)
Difference			0.222			.2877
P-value			.001			.010
Low Alt. * Post	0.123^{*}		0.0930	0.253^{**}		0.273^{**}
	(0.0651)		(0.0680)	(0.118)		(0.121)
High Alt. * Post		-0.122^{**}	-0.0931		-0.0222	0.0624
		(0.0598)	(0.0624)		(0.110)	(0.113)
Difference			0.186			.211
P-value			.0175			.146
Low * Low * Post	0.248^{**}		0.229^{**}	0.491^{***}		0.475^{**}
	(0.115)		(0.116)	(0.183)		(0.184)
High * High * Post		-0.284^{***}	-0.269^{***}		-0.261^{**}	-0.228^{*}
		(0.0761)	(0.0763)		(0.125)	(0.126)
Difference			0.497			.703
P-value			.0002			.0009
Observations	7448	7448	7448	7991	7991	7991

* $p < 0.10$, ** $p < 0.05$, *** $p < .01$

Note: This table compares outcomes before and after the 1780 increase in the malt tax for parishes below the 75th percentile and below the 25th percentile in water quality. The top panel uses the number of available water sources as the measure of water quality, the middle panel uses the altitude of the parish, while the bottom panel estimates the model on the intersection of the two types of water sources. The First three columns use the log of the summer death rate as the dependent variable and estimate the coefficient on high and low quality parishes separately, before including them in the same regression. In column 3, the difference between the high and low quality coefficients is calculated and a p-value on the equality of the coefficients is estimated. Columns 4-6 replicate columns 1-3 using the ratio between summer and winter deaths as the dependent variable. In every specification, controls are included for parish population, local wages, tea imports, parish and year fixed effects as well as a parish linear time trend. The number of winter deaths in that parish is also included to control for factors which impact mortality year round.

Table 2 — Gley Soil - High Tax Interaction Model, 1770-1790

	(1) Smr Dths	(2) Smr Dths	(3) Smr Dths	(4) Ratio
Post - Gley Soil	0.182^{***}	0.177^{***}	0.175^{***}	0.145
	(0.0611)	(0.0610)	(0.0625)	(0.108)
Log Population		-0.935^{***}	-1.111^{***}	0.220
		(0.314)	(0.346)	(0.488)
Log Wage		0.275	0.319	0.513
		(0.245)	(0.250)	(0.369)
Log Tea Imports		0.0617	0.149^{*}	-0.524^{***}
		(0.0826)	(0.0874)	(0.134)
Winter Deaths			0.0490^{***}	
			(0.0154)	
Observations	7775	7753	7448	7991

* $p < 0.10$, ** $p < 0.05$, *** $p < .01$

Note: This table compares outcomes before and after the 1780 increase in the malt tax for parishes with gley soil compared to all other counties. Column 1 includes parish and year fixed effects as well as a parish linear time trend. Column 2 adds controls for population, local wages and tea imports. Column 3 includes the log of winter deaths to control for factors which impact death rates year round, while column 5 replaces the log of summer deaths with the ratio between summer and winter deaths as the dependent variable.

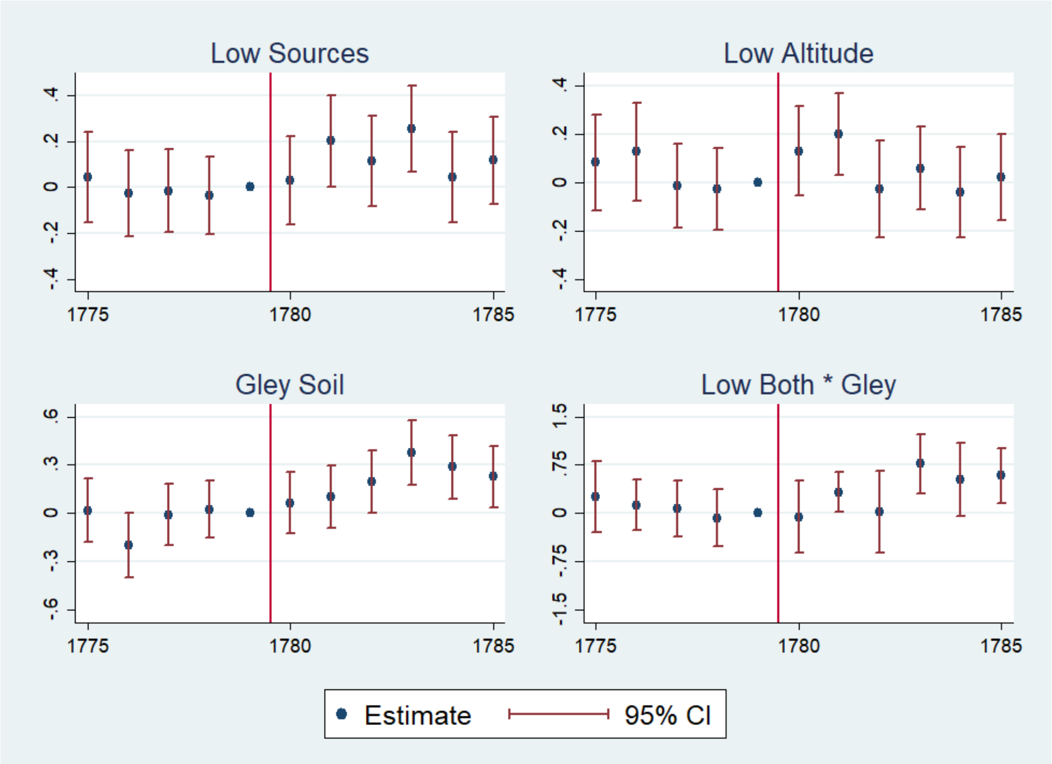
Table 3 — Rainfall - Water Source - Soil Interaction, 1763-1830

	(1) Smr Dths	(2) Smr Dths	(3) Smr Dths	(4) Smr Dths	(5) Ratio
Rain x Sources	0.00330^{**}		0.00288^{*}		
	(0.00161)		(0.00160)		
Rain x Gley		0.00372^{*}	0.00328^{*}		
		(0.00195)	(0.00192)		
RainxGleyxSources				0.00825^{***}	0.00834^{***}
				(0.00221)	(0.00286)
Observations	10315	10315	10315	10315	11125

* $p < 0.10$, ** $p < 0.05$, *** $p < .01$

Note: This table displays estimates of the effect of a rainy barley growing season on different types of parishes which are more or less vulnerable to shocks in beer availability. Column 1 measures the impact on parishes with few nearby water sources, while column 2 estimates the impact on parishes with gley soil, which would otherwise be able to produce large quantities of barley. Column 3 includes both singular interactions, while column 4 includes the joint interaction measuring the effect of rainy barley growing season on parishes with few water sources and gley soil. Column 5 includes the joint interaction and replaces the log of summer deaths on the left hand side with the ratio between summer and winter deaths. All coefficients are positive and significant at .1, which is consistent with our hypothesis. In every specification, controls are included for parish population, local wages, tea imports, parish and year fixed effects as well as a parish linear time trend. The number of winter deaths in that parish is also included to control for factors which impact mortality year round.

Figure 2 — Event Studies - Low Water Quality and Gley Soil



Note: This figure displays event-study estimates comparing the summer death rate in parishes that are more exposed to the malt tax increase. The top left graph displays estimates for parishes with few nearby water sources, the top right graph displays estimates for parishes with low altitude, the bottom right graph displays estimates for parishes which and gley soil, and the bottom right displays estimates for parishes with low water sources, low altitude and gley soil. In each graph, there is relatively little movement before 1780 and no evidence of problematic pretrends, and then increases in summer mortality after the increase in the malt tax.

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A. Online Appendix (Not for Publication)

Table 1 — Parish Water Sources - Malt Tax Interaction Model, 1770-1790

	(1) Winter Deaths	(2) Winter Deaths	(3) Winter Deaths
Low Sources * Post	0.0217		-0.0102
	(0.0559)		(0.0607)
High Sources * Post		-0.0787	-0.0829
		(0.0536)	(0.0582)
Difference			.073
P-value			.27
Observations	7991	7991	7991

* $p < 0.10$, ** $p < 0.05$, *** $p < .01$

Note: This table compares winter mortality before and after the 1780 increase in the malt tax for parishes below the 75th percentile and below the 25th percentile in water quality. The first two columns estimate the coefficient on high and low quality parishes separately, before including them in the same regression in column 3. In column 3, the difference between the high and low quality coefficients is calculated and a p-value on the equality of the coefficients is estimated. In every specification, controls are included for parish population, local wages, tea imports, parish and year fixed effects as well as a parish linear time trend.

Table 2 — Parish Altitude - Malt Tax Interaction Model, 1770-1790

	(1) Winter Deaths	(2) Winter Deaths	(3) Winter Deaths
Low Alt. * Post	-0.0589		-0.0757
	(0.0541)		(0.0582)
High Alt. * Post		-0.0291	-0.0525
		(0.0568)	(0.0610)
Difference			.023
P-value			.73
Observations	7991	7991	7991

* $p < 0.10$, ** $p < 0.05$, *** $p < .01$

Note: This table compares winter mortality before and after the 1780 increase in the malt tax for parishes below the 75th percentile and below the 25th percentile in water quality. The first two columns estimate the coefficient on high and low quality parishes separately, before including them in the same regression in column 3. In column 3, the difference between the high and low quality coefficients is calculated and a p-value on the equality of the coefficients is estimated. In every specification, controls are included for parish population, local wages, tea imports, parish and year fixed effects as well as a parish linear time trend.

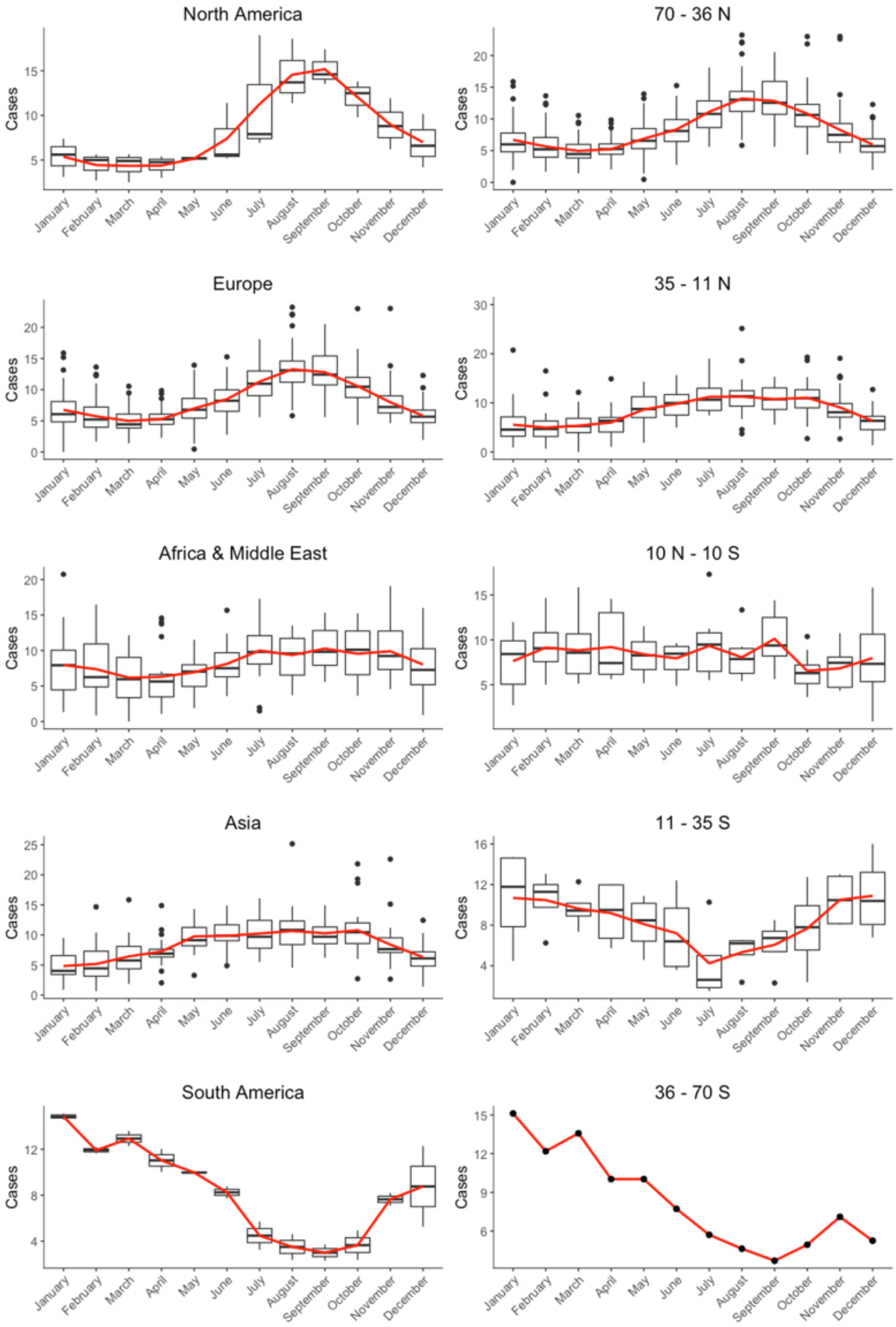
Table 3 — Gley Soil - High Tax Falsification Test, 1770-1790

	(1) Winter Deaths	(2) Winter Deaths	(3) Winter Deaths	(4) Winter Deaths
Post - Gley Soil	0.0560	0.0518	0.0533	0.0549
	(0.0572)	(0.0572)	(0.0574)	(0.0597)
Log Population	-1.567***	-1.553***	-1.556***	-1.787***
	(0.336)	(0.336)	(0.336)	(0.327)
Log Wage		0.324	0.320	0.369*
		(0.216)	(0.217)	(0.222)
Tea Imports x Gley Soil			-0.00885	-0.0167
			(0.0224)	(0.0235)
Summer Deaths				0.0426***
				(0.0134)
Observations	7991	7991	7991	7448

* $p < 0.10$, ** $p < 0.05$, *** $p < .01$

Note: This table compares winter mortality before and after the 1780 increase in the malt tax for parishes with gley soil, which is ideal for growing barley. In the first column population is controlled for, while the second column adds local wages, the third column includes a control for tea imports and the fourth column adds a control for the summer death rate. In every specification, parish and year fixed effects as well as a parish linear time trend.

Figure 1 — Seasonal Dynamics of Enteric and Typhoid Fever



Note: This figure is from Saad et al. (2018) and display seasonal dynamics of enteric and typhoid fever by continent and latitude. The boxplots show the percentage of cases of the different studies for each month of the year and the red line depicts the mean percentage of cases for each month of the year.